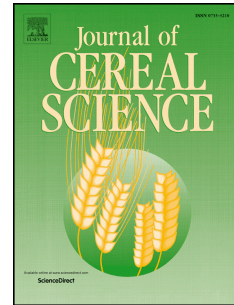


# Accepted Manuscript

The agronomic performance and nutritional content of oat and barley varieties grown in a northern maritime environment depends on variety and growing conditions

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PII: S0733-5210(17)30013-9

DOI: [10.1016/j.jcs.2017.01.005](https://doi.org/10.1016/j.jcs.2017.01.005)

Reference: YJCRS 2268

To appear in: *Journal of Cereal Science*

Received Date: 7 July 2016

Revised Date: 23 November 2016

Accepted Date: 8 January 2017

Please cite this article as: Chappell, A., Scott, K.P., Griffiths, I.A., Cowan, A.A., Hawes, C., Wishart, J., Martin, P., The agronomic performance and nutritional content of oat and barley varieties grown in a northern maritime environment depends on variety and growing conditions, *Journal of Cereal Science* (2017), doi: 10.1016/j.jcs.2017.01.005.

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1

2 **The agronomic performance and nutritional content of oat and barley varieties grown in a**  
3 **northern maritime environment depends on variety and growing conditions**

4

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14

15 **Key words** – nutritional content; maritime environment;  $\beta$ -glucan; variety

16 **Abbreviations** - NDF (Neutral detergent fibre), TKW (Thousand kernel weight),  $\beta$ -glucan ((1-3)(1-4)  $\beta$ -D-  
17 glucan Mixed Link  $\beta$ -glucan), AHDB (Agriculture and Horticulture Development Board), EFSA (European  
18 Food Standards Agency), DEFRA (Department for Environment and Rural Affairs), ANOVA (Analysis of  
19 variance)

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29

## 30 **Abstract**

31 Warmer temperatures and increasing interest in high provenance food and drink products are creating  
32 new opportunities for cereal growing in northern Europe. Nevertheless, cultivation of oats and barley in  
33 these areas for malting and milling remains a challenge, primarily because of the weather, and there are  
34 few reports of their nutritional content from this region. In this study, trials in Orkney compared  
35 agronomic characteristics and nutritional content of recommended UK oat and barley varieties with  
36 Scandinavian varieties over three years. For a subset of varieties, nutritional content was compared with  
37 samples cultivated in more southerly sites. For Orkney, barley was considered a more suitable crop than  
38 oats because varieties matured earlier. In both crops, Scandinavian varieties matured earlier than UK  
39 varieties and some produced comparable yields. The range of values for macronutrients and minerals in  
40 oats and barley in Orkney were similar to those reported previously for other locations, but there were  
41 some significant differences attributable to variety and year. Compared with grain samples from more  
42 southerly locations, oats in Orkney had a significantly lower  $\beta$ -glucan and higher sodium content. The  
43 lower  $\beta$ -glucan may have resulted from higher rainfall and lower temperatures during the months of  
44 grain filling and maturation.

45

## 46 **1. Introduction**

47 Diets high in whole grain cereals are thought to be beneficial for health and several large scale  
48 epidemiological trials have shown their consumption to be associated with a reduction in the risk of type  
49 2 diabetes, obesity, cardiovascular disease (CVD) and colorectal cancer (Murphy et al., 2012; Cho et al.,  
50 2013). The fibre component of cereals is thought to be largely responsible for these actions through a  
51 variety of mechanisms, including: reducing low density lipoprotein (LDL) cholesterol and blood pressure;

52 influencing glucose homeostasis; increasing satiation from a meal; increasing faecal transit time and  
53 lowering the exposure of colonocytes to faecal mutagens and carcinogens; and providing the colonic  
54 microbiota with growth substrates to produce beneficial short chain fatty acid metabolites (Beck et al.,  
55 2009; Othman et al., 2011; Louis et al., 2014).

56 Both oats and barley are high in the soluble fibre (1-3)(1-4)  $\beta$ -D-glucan. Mixed link  $\beta$ -glucan has been  
57 shown to reduce LDL cholesterol and reduce the risk of CVD in clinical trials and currently has several  
58 endorsed health claims worldwide including the European Food Standards Agency (EFSA, 2006).

59 Barley and oats are both important crops in northern areas and their production in this region is likely to  
60 expand with the warmer growing seasons projected to occur as a result of climate change (Bindi and  
61 Olesen, 2011). Northern maritime areas, like Iceland, coastal Norway and parts of Scotland, are also  
62 likely to benefit from these effects, and recent years have seen considerable expansion of barley  
63 cultivation in Iceland (Martin, 2016). Nevertheless, growing barley and oats in such areas remains very  
64 challenging as gales and high winter rainfall often prevent the use of autumn-sown varieties, while high  
65 soil moisture or frozen ground delays cultivation and the planting of spring crops. With cool growing  
66 seasons and the risk of high rainfall at harvest, these areas have a particular requirement for early  
67 maturing varieties, especially if fully mature, dry grain is required for milling or malting.

68 Located about 10 km off the north coast of Scotland, the Orkney archipelago has a hyper-oceanic  
69 climate (Crawford, 2000) and currently grows about 4,500 ha of cereals. Most of this is feed barley for  
70 the local livestock industry, but the expanding market for high provenance food and drink products  
71 (Martin, 2016) has increased interest in local cereals for this purpose. Spring oat and barley varieties in  
72 the United Kingdom's (UK) lists of recommended varieties produced by the Agriculture and Horticulture  
73 Development Board (AHDB, 2016) show only a small variation in days to maturity. Consequently earlier

74 maturing varieties sourced from Scandinavia are being tested in Orkney by the Agronomy Institute of  
75 the University of the Highlands and Islands (UHI).

76 The environment in which cereals are grown is known to affect their nutritional composition, and  
77 studies have found differences in the protein, fat and  $\beta$ -glucan content of oats and barley grown in  
78 different environments (Zhou et al., 1999; Redaelli et al., 2013). There are no detailed reports on the  
79 composition of oats and barley grown in hyper-oceanic climates like Orkney's. The present study reports  
80 the chemical composition and agronomic performance of early and later maturing varieties of oats and  
81 barley grown in Orkney between 2012 and 2014. For a subset of varieties, nutritional composition in  
82 Orkney was compared with that of the same varieties grown in more southerly parts of the UK.

83

## 84 **2. Materials and methods**

### 85 *2.1 Orkney field trials*

86 Six oat and six barley varieties were grown in separate trials over three consecutive growing seasons  
87 from 2012 to 2014. The trials were located at Orkney College UHI (58° 59' N and 2° 57' W) on sandy  
88 loam soil. Trials used a randomised block design with five replicates. Barley varieties included Bere (an  
89 early maturing Scottish landrace), three Scandinavian varieties obtained from Lantmännen SW Seed AB  
90 (Vilde, Kannas and Vilgott), and two recommended (AHDB, 2016) UK varieties (Waggon for feed and  
91 Concerto for malting). Oat varieties included three Scandinavian varieties from Lantmännen SW Seed AB  
92 (Haga, Belinda, and Betania) and two recommended (AHDB, 2016) UK varieties (Firth and Canyon) and  
93 Lennon, a naked oat. Varieties were planted in plots 20 m long and 3 m wide with a plant population of  
94 350 plants m<sup>-2</sup> for barley and 400 plants m<sup>-2</sup> for oats. Fertilizer was applied to both cereals at planting  
95 each year; oats received 50-60 kg ha<sup>-1</sup> yr<sup>-1</sup> of nitrogen and phosphorus (as P<sub>2</sub>O<sub>5</sub>) and 67-91 kg ha<sup>-1</sup> yr<sup>-1</sup> of

106 potassium (as  $K_2O$ ); barley received  $65 \text{ kg ha}^{-1} \text{ yr}^{-1}$  of nitrogen and phosphorus (as  $P_2O_5$ ) and 87-105 kg  
107  $\text{ha}^{-1} \text{ yr}^{-1}$  of potassium (as  $K_2O$ ). The planting dates and inputs used are specified in Supplementary Table  
108 S1. Varieties were harvested when they reached senescence and usually when grain moisture content  
109 was below 25%. Plots were harvested with a Sampo combine with 2.3 m cutter bar and the weight of  
110 grain per plot measured. An 800 g sample of grain was collected from each plot and a 200 g subsample  
111 from this was used for determining grain moisture and thousand kernel weight (TKW) which was  
112 determined with a seed counter (Contador). TKW is often used as an indicator of grain quality in both  
113 barley and oats; in barley, it is correlated with grain plumpness and is a good indicator of starch in the  
114 kernel (Newman and Newman, 2008). The remaining 600 g sample was dried in an oven for 48 h at  $35^\circ\text{C}$   
115 and retained for the nutritional analyses. Grain yield ( $\text{t ha}^{-1}$ ) per plot was calculated at 15 % moisture  
116 content from the fresh weight of grain harvested and the laboratory determinations of grain moisture.  
117 Poor weather resulted in lodging of oats in the 2012 harvest and only Haga could be machine-harvested;  
118 all other varieties were hand-harvested to obtain samples for analysis.

109 One composite soil sample was collected from each of the oat and barley trials in February 2012, 2013  
110 and 2014 and consisted of the mixed soil from 8 cores (0 - 30 cm depth). Samples were analysed by NRM  
111 laboratories (Bracknell, England) and results are summarised in Supplementary Table S2. Data for  
112 precipitation and temperature during each growing season were obtained for Kirkwall airport, about 6  
113 km from the trial site from <http://en.tutiempo.net/climate/europe.html> and are summarised in  
114 Supplementary Table S3.

## 115 *2.2 Other field trials*

116 In additional trials in the same growing seasons, two recommended UK (AHDB, 2016) barley varieties  
117 (Waggon and Concerto) were grown by the James Hutton Institute at Balruddery near Dundee in  
118 Scotland ( $56^\circ 28'N$  and  $-3^\circ 4'W$ ), and three recommended UK (AHDB, 2016) oat varieties (Lennon, Firth

119 and Canyon) were grown by Aberystwyth University in Wales at Morfa (52° 54'N and -4° 32'W) and in  
120 the north of England at Berwick-upon-Tweed (55° 45'N and -2° 0'W. Weather data for Dundee were  
121 obtained from an automatic weather station at the trial site and for the other sites from the closest  
122 stations listed in the TuTiempo.net database (<http://en.tutiempo.net/climate/europe.html>). These sites  
123 were Gogarbank for Berwick-upon-Tweed and Aberporth for Morfa. For each site, total rainfall and  
124 degree days were calculated from the date of planting to that of harvesting. Degree days were  
125 calculated from each day's average temperature using a base temperature of 0 °C. From each site, a 100  
126 g grain sample was obtained from each variety and used for the nutritional analyses.

### 127 *2.3 Processing of oat and barley samples*

128 Oat and barley grains of all varieties were processed in the same way and were first heat-treated to  
129 deactivate endogenous lipase and  $\beta$ -glucanase enzymes. Samples were placed in uncovered containers  
130 and steamed in an autoclave for 10 min and then incubated at room temperature for 48 h to allow  
131 moisture to equilibrate. They were then dehulled for 30 sec using a laboratory thresher (Streckel and  
132 Schrader, Hamburg, Germany) and barley underwent a second dehulling to replicate pearling. After a 15  
133 min cooling period, samples were milled into a fine flour using a freeze mill (Spex, Certi Prep 6800  
134 Freeze Mill). Milling consisted of 2 min of milling followed by a 2 min cooling period and a final 2 min  
135 milling period. Flours were then stored refrigerated between 2 and 8 °C and analyses were completed  
136 within 6 months.

### 137 *2.4 Nutritional analyses*

#### 138 *2.4.1 Macronutrient analysis by near-infrared reflectance spectroscopy (NIRS)*

139 Compositional analysis (Ash, Lipid, Protein, Starch, Sugar and fibre as Neutral Detergent Fibre (NDF)) was  
140 carried out at the Royal Zoological Society of Scotland (Edinburgh) using near-infrared spectroscopy

141 (NIRS). Each flour sample was analysed in triplicate and the mean value was used in the statistical  
142 analysis. Since differences in macronutrient content between plots of the same variety were negligible  
143 (Supplementary Table S4), grain samples from plots of the same variety in each separate year were  
144 pooled prior to further analysis. The mean nutrient composition of varieties presented in Tables 2 to 5  
145 were calculated from combined data across the three growing seasons. The  $\beta$ -glucan content of grains  
146 were analysed in triplicate, enzymatically, according to the method of McCleary and Codd (1991), using  
147 a commercially available kit (Megazyme International Ireland, Bray, Ireland), following the  
148 manufacturer's instructions.

#### 149 *2.4.2 Mineral analysis by inductively coupled plasma-mass spectrometry (ICP-MS)*

150 Mineral composition was quantified using inductively coupled plasma - mass spectrometry (ICP - MS) at  
151 the Rowett Institute. All samples were analysed in duplicate and the mean was used for the statistical  
152 analysis. The following minerals were quantified: Magnesium (Mg), Phosphorus (P), Potassium (K),  
153 Calcium (Ca), Sodium (Na), Manganese (Mn), Iron (Fe), Copper (Cu), Zinc (Zn), Chromium (Cr), Cobalt  
154 (Co), Nickel (Ni), Selenium (Se), Molybdenum (Mo), Cadmium (Cd) and Palladium (Pd). Mean mineral  
155 composition of a cultivar was determined by combining data across the three growing seasons. This data  
156 is summarised in Supplementary Tables S5 and S6.

#### 157 *2.5 Statistical analysis*

158 Data were analysed with Genstat 13<sup>th</sup> Edition, release 17.1 (VSN International Ltd, Hemel Hempstead,  
159 Herts., UK). Grain yield and TKW from the Orkney trial used generalised analysis of variance with blocks  
160 as replicates, and with plot, year and their interaction nested within replicates. Treatment terms were  
161 variety, year and their interaction. Three years of data were analysed for the barley trial, but only two  
162 years (2013 and 2014) for the oat trial. Nutritional composition analysis including NIRS analysis,  $\beta$ -glucan  
163 content, mineral composition and comparison between locations were analysed by two-way ANOVA



164 with variety and year as treatment factors. For all ANOVA analyses, significant differences between  
165 factors were determined by the F - test at  $p < 0.05$ . When significant, this was followed by an  
166 unprotected Fisher's exact test at  $p < 0.05$  to identify significantly different treatment means.  
167 Correlation coefficient analysis was performed to determine the correlation between rainfall and degree  
168 days over the growing season and nutritional composition of varieties and between the agronomic traits  
169 TKW and yield, and nutritional composition. Correlations were considered significant when the  
170 correlation coefficient achieved a significance level of  $p < 0.05$ .

171

### 172 **3. Results and discussion**

#### 173 *3.1 Orkney agronomy trials*

174 Harvest data for the oat and barley trials in Orkney are summarised for 2012 to 2014 in Table 1. In all  
175 years, barley required fewer days and degree days from planting to harvest than oats and the averages  
176 over varieties and years for barley and oats, respectively, were 143 and 160 days and 1659 and 1858  
177 degree days. The earliest maturing barley varieties were Bere, Vilde and Kannas which required  
178 averages of 1562 to 1595 degree days to harvest compared with 1821 and 1836 degree days for the  
179 earliest oat varieties, Haga and Canyon. The advantage of early varieties under Orkney conditions was  
180 demonstrated in 2012, when Haga was the only oat variety that ripened sufficiently early to be  
181 harvested in good weather; varieties ripening later were either too wet or too badly lodged to harvest.  
182 The number of days and degree days to harvest decreased by year from 2012 to 2014 (Table 1),  
183 reflecting an increase in the average temperature of the growing season (1 April to 30 September) -  
184 10.4, 11.3 and 12.1 °C for 2012, 2013 and 2014, respectively.

185 Average yields for oats were significantly higher in 2014 (5.27 t ha<sup>-1</sup>) compared to 2013 (4.66 t ha<sup>-1</sup>) (p =  
186 0.001), and significant differences in grain yields occurred between varieties of both oats and barley (p <  
187 0.05). The highest thousand kernel weight (TKW) for both oats and barley (41.8 and 44.9 g respectively)  
188 occurred in 2013. The 2012 growing season was particularly poor and had the lowest yields and TKW for  
189 barley and also for Haga, the only oat variety which was harvested in all years. Amongst oats, Lennon  
190 had significantly lower yields and TKW than the other varieties which can be attributed to it being a  
191 naked variety. The highest yielding oat varieties were Canyon in 2014 and Haga in 2013. Canyon had the  
192 highest TKW in both 2013 and 2014. Amongst barley varieties, Bere had the lowest yields in all years,  
193 reflecting its status as a landrace which has not been improved by plant breeding (Martin et al., 2009).  
194 Bere and Vilde are both 6-row barleys and their TKWs were always lower than those of the 2-row  
195 varieties. The highest yielding variety differed from year to year and was Vilgott, Kannas and Waggon in  
196 2012, 2013 and 2014, respectively. In contrast, Kannas and Waggon were always the varieties with the  
197 highest TKW. The average annual grain yields of the Scandinavian varieties of both oats and barley are  
198 lower than those reported for other similar Scandinavian varieties grown near Helsinki in Finland  
199 (Peltonen-Sainio et al., 2008), but the latter were grown with higher levels of nitrogen fertiliser and the  
200 growing season is also normally warmer in Helsinki. However, the average TKWs of the Scandinavian  
201 varieties grown in Orkney were higher than the averages of those in Finland, especially for oats.

202 For TKW and yield, there were significant interactions (p < 0.001) between variety and year for both oats  
203 and barley showing that some varieties performed better in some years than others. For example,  
204 Kannas was relatively low yielding in 2012 and 2014, but had the highest yield in 2013. In Scotland,  
205 barley and oat national yields from 1963-2005 were both correlated negatively with rainfall in July and  
206 positively with total sunshine over the season (Brown, 2013). Variations in yield between varieties may  
207 result from varietal differences in ability to adapt to seasonal variations in these and other weather  
208 variables. Average Scottish yields for spring barley were 5.6 t ha<sup>-1</sup> from 2012 to 2014 and 6.0 t ha<sup>-1</sup> for

209 spring oats from 2013 to 2014 (DEFRA, 2015). In comparison, the average yields in Orkney for the  
210 recommended UK oat (Canyon and Firth) and barley (Waggon and Concerto) varieties were about 5-12%  
211 less over these years, probably reflecting Orkney's more challenging growing conditions. Compared with  
212 these recommended varieties, the Scandinavian varieties Vilde, Kannas and Haga had similar yields and  
213 had the advantage of maturing earlier. Vilde and Haga had lower TKW, however, which might limit their  
214 acceptability for off-farm commercial use in Scotland. Nevertheless, because of their earliness, both  
215 varieties could be useful in the northern part of the country for particular, on-farm purposes like  
216 undersowing with grass or for making early whole-crop silage.

### 217 *3.2 Macronutrient composition of oats and barley grown in Orkney*

218 The macronutrient composition of oat and barley grains produced in Orkney between 2012 and 2014  
219 are summarised in Table 2 and are similar to previously reported values (Peterson et al., 1975;  
220 Saastamoinen et al., 1992; Zhou et al., 1999; Andersson et al., 2008; Doehlert et al., 2013). There were  
221 significant differences between barley varieties for all macronutrients tested ( $p < 0.05$ ). In oats there  
222 was a significant difference between varieties for  $\beta$ -glucan ( $p = 0.001$ ) and near-significant differences  
223 between varieties for ash ( $p = 0.056$ ), sugar ( $p = 0.088$ ) and fat (0.051). The most abundant nutritional  
224 component of oat and barley grains was starch, followed by either NDF or protein and then fats.  
225 Waggon and Concerto barley contained a high starch and low protein content which is particularly  
226 desirable in a malting barley variety like Concerto.

227 The levels of NDF and  $\beta$ -glucan within oats and barley (NDF, 5-24 g per 100 g;  $\beta$ -glucan, 2-5 g per 100 g)  
228 corresponded to the ranges previously reported (Andersson et al., 2008; Ward et al., 2008; Doehlert et  
229 al., 2013) and the ranges of  $\beta$ -glucan in the two cereals were similar. Bere barley and Haga oats both  
230 had particularly low  $\beta$ -glucan content (Bere, 2.27 g per 100 g; Haga, 2.59 g per 100 g) and were both  
231 early maturing varieties. The Scandinavian variety Kannas had the highest  $\beta$ -glucan content of all the

232 barley varieties (3.60 %), was early maturing and gave reasonable yields. Modern Scandinavian varieties  
233 could therefore be valuable crops both nutritionally and agronomically for northern maritime areas. Oat  
234  $\beta$ -glucan content did not vary significantly between years, and other studies have indicated that  
235 environment may be more important in determining the molecular weight of  $\beta$ -glucan rather than the  
236 total content (Andersson and Börjesdotter, 2011).

237 Previous studies in oats and barley (MacArthur and D'Appolonia, 1979; Chatterton et al., 2006) reported  
238 free sugar to be less than 2.3 g per 100 g, while we found values as high as 5.63 g per 100 g in oats and  
239 3.44 g per 100 g in barley. However, free sugars are often either unreported or are contained within the  
240 total carbohydrate value which includes starch and free sugars. The mean total of all the macronutrients  
241 was between 92 and 106 %. Analysis of the macronutrient content of varieties averaged over years  
242 showed significant differences (see  $p$  year in Table 2; mean values for each year are given in Table 6) for  
243 ash, protein, starch, NDF and fat in oats and for protein, NDF, and  $\beta$ -glucan in barley ( $p < 0.05$ ). The  
244 difference in sugar between years in barley was nearly significant ( $p = 0.073$ ). It is likely that some of  
245 these differences were due to annual variations in the weather which are considered later. The ash  
246 component is thought to contain many of the micronutrients and the ranges encountered were 1.6-2.5 g  
247 per 100 g in oats and 1.0-2.2 g per 100 g in barley.

248 In common with results from other research on barley in northern areas (Peltonen-Sainio et al., 2012),  
249 there was a significant negative correlation between protein and both yield ( $p < 0.05$ ; correlation  
250 coefficient, -0.492) and TKW ( $p < 0.01$ ; correlation coefficient, -0.742) for barley. Particularly high grain  
251 protein content and low yields and low TKW occurred in 2012 which may have been caused by the low  
252 growing season temperature and low sunshine hours in July and August limiting photosynthesis and  
253 starch accumulation more than nitrogen uptake. This contrasts with drier regions, where high grain  
254 protein is associated with water stress pre-anthesis, or during grain filling (Bertholdsson, 1999). The

255 negative correlation between yield and protein was linked to the finding that the highest yielding  
256 varieties were those with a high starch and low protein content (Waggon and Concerto) while the  
257 lowest yielding varieties tended to be those with low starch and high protein content (Bere and Kannas).  
258 Previous studies have shown TKW to be both positively and negatively associated with  $\beta$ -glucan (Zhou et  
259 al., 1999; Andersson and Börjesdotter, 2011), but no significant correlation was found in the Orkney trial  
260 for either oats or barley. Although the design of the trials did not allow a statistical comparison of oats  
261 and barley, averaged over varieties and years the concentrations of fats and sugar were higher in oats,  
262 while NDF and starch were higher in barley.

### 263 *3.3 Mineral composition of oats and barley grown in Orkney*

264 The content of abundant minerals in grains of oat and barley varieties grown in Orkney is summarised in  
265 Table 3 and that of several trace elements in Supplementary Table S5. The most abundant minerals  
266 detected were potassium, phosphorus, magnesium, calcium and sodium while manganese, iron, copper  
267 and zinc were all present in low, relatively similar amounts (< 6 mg per 100 g for both oats and barley).  
268 Other studies (Peterson et al., 1975; Doehlert et al., 2012) have also reported magnesium, phosphorus,  
269 potassium and calcium as the most abundant minerals in oats and barley. The high levels of phosphorus  
270 and potassium probably reflect their application in fertilisers. The trace elements chromium, cobalt,  
271 nickel, and molybdenum were all present at less than 2  $\mu$ g per 100 g of cereal, while negligible amounts  
272 of selenium, cadmium and lead were detected. There were significant differences between varieties of  
273 oats for magnesium, phosphorus, calcium, copper, zinc, and molybdenum ( $p < 0.05$ ) and varieties of  
274 barley for phosphorus, sodium, manganese, copper, and zinc ( $p < 0.05$ ). However, differences in the  
275 minerals manganese, copper, zinc, nickel, and molybdenum were small and were based upon  
276 measurements of very low levels (less than 4 mg per 100g in most cases). In both oats and barley, some

277 varieties seemed better at accumulating minerals than others, with the highest concentrations often  
278 occurring in Haga, Bere and Kannas and the lowest in Vilgott and Firth.

279 In several cases, the mineral content of oat and barley varieties was significantly affected by the year.  
280 There were significant differences in the annual means for magnesium, phosphorus, potassium and  
281 calcium for oats ( $p < 0.05$ ), and for all minerals except iron, nickel and chromium for barley ( $p < 0.05$ ).  
282 Since soil analyses showed only small differences in soil mineral content between years (Supplementary  
283 Table S2), this may reflect differences in the availability of soil nutrients or the growth of roots between  
284 years.

#### 285 *3.4 Influence of location and weather on the nutrient composition of oats and barley*

286 The nutritional content of some of the oat and barley varieties grown in Orkney was compared with that  
287 of the same varieties grown further south in the UK between 2012 and 2014. Tables 4 and 5,  
288 respectively, summarise the macronutrient and mineral composition of the oat varieties Canyon, Firth  
289 and Lennon grown in Orkney, Morfa and Berwick-upon-Tweed and the barley varieties Concerto and  
290 Waggon grown in Orkney and Dundee.

291 There were significant differences between oat varieties for  $\beta$ -glucan (lowest in Firth), starch (highest in  
292 Lennon), sugar (lowest in Canyon) and fat content (highest in Lennon) ( $p < 0.05$ ) and near-significant  
293 differences for protein ( $p = 0.086$ ), NDF ( $p = 0.051$ ), starch ( $p = 0.091$ ) and sugar ( $p = 0.074$ ). The only  
294 macronutrient differing significantly between locations was  $\beta$ -glucan ( $p = 0.011$ ), which was lowest for  
295 all varieties when grown in Orkney. These results suggest that the Orkney environment may not be  
296 optimal for growing oats for a high  $\beta$ -glucan market. Nevertheless, this disadvantage might be mitigated  
297 by careful variety selection – for example, the Scandinavian variety Betania had a significantly higher  $\beta$ -  
298 glucan content than any of the other varieties grown in Orkney (Table 2), with concentrations similar to  
299 the highest values for oats grown further south. However, the relationship between climate and  $\beta$ -

300 glucan is complex (Redaelli et al., 2013) and studies over more seasons, more varieties and on other  
301 soils are required to investigate this further. The ash, protein, starch, NDF and  $\beta$ -glucan content of oats  
302 was also affected by the growing year ( $p < 0.05$ ). Comparing the barley varieties grown in Orkney and  
303 Dundee, no significant differences were detected for either variety or location, although several  
304 differences were almost significant (Table 4). Year, however, influenced several macronutrients in barely  
305 including ash, protein, and NDF ( $p < 0.05$ ). Previous studies have shown that nutritional content can be  
306 affected by differences between growing sites, variety and agronomic factors (Zhou et al., 1999;  
307 Doehlert et al., 2013; Redaelli et al., 2013; Sikora et al., 2013). It is possible that the environmental  
308 differences between the sites in this study may not have been diverse enough to result in larger  
309 differences in nutrient content.

310 For minerals, there were significant differences between oat varieties in potassium, calcium,  
311 manganese, and copper ( $p < 0.05$ ) (Table 5). Potassium, sodium and zinc were significantly influenced by  
312 location ( $p < 0.05$ ), with the potassium content being lowest at Morfa, the sodium content highest in  
313 Orkney and the zinc content highest at Berwick-upon-Tweed (Table 5). In the case of sodium, this  
314 probably resulted from the Orkney trial site being only about 1 km from the sea. The difference in zinc  
315 content between the sites was low (less than 0.2 mg) and should be interpreted with caution. The  
316 content of the following minerals also differed with harvesting year: magnesium, phosphorus, calcium,  
317 manganese, iron, copper and zinc. In most cases these were highest in 2014 and often lowest in 2012. In  
318 barley, the iron content was significantly higher ( $p = 0.03$ ) in Orkney compared to Dundee and may  
319 reflect the high levels of iron which occurred in soils at this trial site (Supplementary Table S2). Analysis  
320 of trace mineral composition (Supplementary Table S6) identified few significant differences related to  
321 location or variety, with the exception of a higher content of molybdenum in Waggon than Concerto  
322 barley. The content of some minerals (phosphorus, potassium, magnesium, copper and zinc) in barley  
323 flour (Table 5) was also significantly affected by year, with the highest concentrations of phosphorus,

324 potassium, calcium, sodium, and manganese found in 2014. It is likely that the high concentrations of  
325 some minerals which occurred in 2014 in both barley and oats is related to weather patterns but more  
326 years of data would be required to clarify this. Apart from a significantly lower  $\beta$ -glucan content in oats  
327 and minor differences in mineral content for both oats and barley, these analyses indicated that the  
328 nutritional content of oats and barley in Orkney was not very different from that of the same varieties  
329 grown at more southerly UK sites. Nevertheless, the few near-significant differences may justify further  
330 investigation.

331 The annual macronutrient content of oats and barley averaged over varieties at each site together with  
332 growing season rainfall and degree days is shown in Table 6. There were several significant correlations  
333 between rainfall and degrees days and nutrient content. Rainfall had a strong positive correlation with  
334 protein concentration for oats and barley in Orkney, and oats at Morfa. At these sites, protein  
335 concentrations were highest in the wettest year, 2012, and were lowest in the driest year (2014 in  
336 Orkney and 2013 at Morfa). Degree days, however, was negatively correlated with protein content for  
337 oats and barley in Orkney and barley at Dundee, but positively correlated with protein in oats grown in  
338 Berwick-upon-Tweed and Morfa. Weather factors were one of the principal drivers for a large  
339 environmental effect on grain protein concentration reported for oats and barley grown in Finland, and  
340 exceeded the effect of genotype (Peltonen-Sainio et al., 2012). In Orkney, the fat content of oats was  
341 correlated positively with degree days but negatively with rainfall. Starch and NDF content often showed  
342 the opposite relationships with rainfall and degree days. Rainfall showed a positive association with the  
343 starch content of oats grown in Orkney and barley grown in Dundee while, NDF was negatively  
344 correlated with rainfall for oats and barley grown in Orkney and barley in Dundee. In contrast, degree  
345 days was negatively correlated with starch but positively correlated with NDF for oats in Orkney. It can  
346 also be seen that the highest starch concentrations occurred in all trials in 2012 and were accompanied  
347 by particularly low levels of NDF. Conversely, the lowest starch contents mostly occurred in 2013 and



348 were accompanied by the highest concentrations of NDF. Previously, Becker et al. (1995) and Tiwari and  
349 Cummins (2009) have suggested that non-starch polysaccharide synthesis competes for the same  
350 glucose molecules that are required for the biosynthesis of starch and therefore an increase in starch  
351 content may be at the expense of the fibre component (Beckles and Thitisakul, 2013). It may therefore  
352 be that the opposite correlations which were found above between starch and NDF and weather  
353 variables, reflect this competition. The dynamic between starch and NDF may also go some way to  
354 explaining the relationship between rainfall, temperature and protein content. Carbohydrate makes up  
355 the largest proportion of the grain, and when weather conditions constrain starch and NDF synthesis,  
356 the proportion of protein within the grain increases. This would help to explain the negative correlations  
357 seen in Orkney between protein concentration and both yield and TKW.

358 Although significant correlations between  $\beta$ -glucan and rainfall and degree days were only found for  
359 oats grown at Morfa, significant differences between  $\beta$ -glucan attributable to location are reported in  
360 Table 4 for three varieties of oats. For these varieties,  $\beta$ -glucan was highest at Berwick-upon-Tweed (3.5  
361 g / 100g) and lowest in Orkney (3.1 g / 100 g). The main differences in growing season weather between  
362 these two locations were the higher rainfall and lower temperatures in Kirkwall. Differences were  
363 particularly marked during the months of grain filling and maturation (August to September) with much  
364 higher rainfall in Orkney (average, 203 mm for 2012 to 2014 compared with 141 mm at Berwick-upon-  
365 Tweed) and higher temperatures at Berwick-upon-Tweed (average, 14.5 °C compared with 13.0 °C in  
366 Orkney). Warmer, drier conditions were also found to favour  $\beta$ -glucan production by Andersson and  
367 Börjesdotter (2011), although the opposite has also been reported by Doehlert et al. (2013), while  
368 Redaelli et al. (2013) reported the highest  $\beta$ -glucan content under intermediate temperature and rainfall  
369 conditions. In barley, protein content is an important determinant of end-use with low protein and high  
370 starch especially desirable for malting. Data in Table 5 for Concerto and Waggon suggest that conditions  
371 in Orkney may favour a higher protein content than those in Dundee. Comparison of the weather data

372 for the two sites from 2012 to 2014 showed a consistent pattern of lower rainfall in Orkney from May to  
373 July (average, 128 mm compared with 210 mm in Dundee), but higher rainfall from August to September  
374 (average, 203 mm compared with 109 mm in Dundee). Growing season average monthly temperatures  
375 were all higher in Dundee, but especially for the period May to July (average 11.7°C in Orkney and  
376 12.2°C in Dundee).

#### 377 **4. Conclusions**

378 Agronomy trials and detailed nutritional analyses were carried out for a diverse group of barley and oat  
379 varieties grown in Orkney and at other sites in the UK. There has been no previous report of the  
380 nutritional content of oats and barley grown in hyper-oceanic climates like Orkney's. These trials  
381 indicated that Scandinavian early maturing varieties of both oats and barley are suitable for growing in  
382 the north of Scotland and the nutritional analyses showed that some of these had significantly higher  $\beta$ -  
383 glucan content than the recommended UK varieties grown in the trial. Since Scandinavian varieties were  
384 not included in trials in more southerly locations where oat  $\beta$ -glucan contents were generally higher, it  
385 would be useful to test some of these varieties in these locations to assess the impact on  $\beta$ -glucan  
386 levels. Significant varietal differences were found in both oats and barley for most macronutrients and  
387 abundant minerals, demonstrating the importance of selecting varieties for specific end-uses. Weather  
388 conditions appeared to affect the nutrient content of the varieties, with the level of several nutrients  
389 varying from year to year. Future work should investigate the influence of weather factors before and  
390 after the grain filling period on nutritional content. It would also be valuable to screen a wider range of  
391 Scandinavian varieties for growing in the north of Scotland.

392 Compared with the other barley varieties, the Scottish landrace Bere, which has a tradition of use for  
393 milling into beremeal and also for brewing and distilling (Martin et al., 2009), had low  $\beta$ -glucan, but high  
394 fat, sugar and protein; it also contained the highest concentrations of several minerals. In spite of the

395 weather-related challenges of growing oats and barley in Orkney, the nutritional analyses showed few  
396 statistically significant differences between the nutritional content of their grains from Orkney  
397 compared with those from trials in more southerly parts of the UK. The main exception was  $\beta$ -glucan,  
398 which was lower in Orkney oats. Although not significant, it was also noted in barley that protein tended  
399 to be higher in Orkney, which may make it harder to produce good quality malting barley. It is not clear  
400 to what extent the results from Orkney can be extrapolated to more northern maritime locations like  
401 Iceland, the Faroes and coastal Norway, but analyses of a small number of samples from the same  
402 varieties of barley grown in these areas in 2014 showed a higher sugar, but lower starch content in the  
403 samples from Orkney. It is therefore likely that differences will occur, and this is under investigation.

#### 404 **5. Acknowledgements**

405 Funding for this research came from the Scottish Government's Rural and Environment Science and  
406 Analytical Services Division (RESAS) through their support for this Strategic Partnership project. We  
407 are also grateful to Ingvar Andersson at Lantmännen SW Seed AB for supplying seed of the Scandinavian  
408 varieties for the trials each year and to the seed merchant William Shearer (Kirkwall) for importing it.  
409 We are indebted to Grietje Holtrop from Biomathematics and Statistics Scotland for her help with  
410 statistical analysis. Andy Beer (The Royal Zoological Society, Edinburgh) performed all NIRS analysis and  
411 Gill Campbell (Rowett Institute of Nutrition and Health) performed the mineral content analysis. The  
412 Centre for Sustainable Cropping platform is supported through Scottish Government Underpinning  
413 Capacity funding. The Agronomy Institute acknowledges support from the Northern Periphery and Arctic  
414 Programme's Northern Cereals project in preparing this publication.

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**Table 1.** Days and degree days from planting to harvesting, thousand kernel weight (TKW) and yield of oat and barley varieties grown in Orkney, from 2012 to 2014. TKW and grain yield are presented at 15% grain moisture.

Cereal / Variety	Days to harvest				Degree days to harvest				TKW (g)				Grain yield (t ha <sup>-1</sup> )			
	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014
<b>Oats</b>																
Haga	164	163	142	156	1822	1852	1788	1821	36.9	41.4 <sup>c</sup>	38.9 <sup>c</sup>	40.2 <sup>c</sup>	5.18	5.32 <sup>c</sup>	5.62 <sup>c</sup>	5.47 <sup>cd</sup>
Belinda	169	163	147	160	1861	1852	1854	1856	-	43.6 <sup>d</sup>	42.5 <sup>d</sup>	43.0 <sup>d</sup>	-	5.01 <sup>d</sup>	5.51 <sup>c</sup>	5.26 <sup>c</sup>
Betania	197	163	147	169	2058	1852	1854	1921	-	46.2 <sup>e</sup>	42.6 <sup>d</sup>	44.4 <sup>e</sup>	-	4.67 <sup>e</sup>	4.62 <sup>b</sup>	4.65 <sup>b</sup>
Canyon	170	163	142	158	1869	1852	1788	1836	-	47.2 <sup>e</sup>	43.8 <sup>d</sup>	45.5 <sup>e</sup>	-	4.82 <sup>e</sup>	6.18 <sup>e</sup>	5.50 <sup>d</sup>
Firth	169	163	147	160	1861	1852	1854	1856	-	38.7 <sup>b</sup>	35.9 <sup>b</sup>	37.3 <sup>b</sup>	-	4.68 <sup>b</sup>	5.88 <sup>d</sup>	5.28 <sup>c</sup>
Lennon	170	163	147	160	1869	1852	1854	1858	-	33.8 <sup>a</sup>	28.3 <sup>a</sup>	31.1 <sup>a</sup>	-	3.49 <sup>a</sup>	3.83 <sup>a</sup>	3.66 <sup>a</sup>
Mean	173	163	145		1890	1852	1832		-	41.8 <sup>x</sup>	38.7 <sup>y</sup>		-	4.66 <sup>x</sup>	5.27 <sup>y</sup>	
									p variety			<b>&lt;0.001</b>	p variety			<b>&lt;0.001</b>
									p year			<b>&lt;0.001</b>	p year			<b>&lt;0.001</b>
									p variety x year			<b>0.018</b>	p variety x year			<b>&lt;0.001</b>
<b>Barley</b>																
Vilde	145	146	121	137	1638	1632	1515	1595	37.7 <sup>c</sup>	39.3 <sup>b</sup>	38.4 <sup>a</sup>	38.5 <sup>b</sup>	5.02 <sup>bc</sup>	5.00 <sup>bc</sup>	5.69 <sup>c</sup>	5.24 <sup>b</sup>
Kannas	145	146	121	137	1638	1632	1515	1595	39.3 <sup>c</sup>	48.9 <sup>d</sup>	48.3 <sup>c</sup>	45.5 <sup>e</sup>	4.81 <sup>b</sup>	5.50 <sup>d</sup>	4.83 <sup>b</sup>	5.05 <sup>b</sup>
Vilgott	154	154	127	145	1733	1743	1583	1686	35.3 <sup>b</sup>	46.0 <sup>c</sup>	42.4 <sup>b</sup>	41.2 <sup>c</sup>	5.51 <sup>c</sup>	5.12 <sup>bcd</sup>	5.09 <sup>b</sup>	5.24 <sup>b</sup>
Bere	146	146	116	136	1600	1632	1453	1562	30.2 <sup>a</sup>	37.1 <sup>a</sup>	35.9 <sup>a</sup>	34.3 <sup>a</sup>	3.59 <sup>a</sup>	4.38 <sup>a</sup>	4.09 <sup>a</sup>	4.05 <sup>a</sup>
Concerto	164	154	136	151	1822	1743	1711	1758	34.5 <sup>b</sup>	48.0 <sup>d</sup>	44.9 <sup>b</sup>	42.5 <sup>d</sup>	4.99 <sup>bc</sup>	5.33 <sup>cd</sup>	5.52 <sup>c</sup>	5.28 <sup>b</sup>
Waggon	164	154	136	151	1822	1743	1711	1758	38.4 <sup>c</sup>	50.2 <sup>e</sup>	48.2 <sup>c</sup>	45.6 <sup>e</sup>	4.96 <sup>bc</sup>	4.83 <sup>ab</sup>	5.74 <sup>c</sup>	5.18 <sup>b</sup>
Mean	153	150	126		1709	1688	1581		35.9 <sup>x</sup>	44.9 <sup>z</sup>	43.0 <sup>y</sup>		4.83 <sup>x</sup>	5.03 <sup>y</sup>	5.16 <sup>y</sup>	
									p variety			<b>&lt;0.001</b>	p variety			<b>&lt;0.001</b>
									p year			<b>&lt;0.001</b>	p year			<b>0.003</b>
									p variety x year			<b>&lt;0.001</b>	p variety x year			<b>&lt;0.001</b>

Different letters indicate significant differences at  $p < 0.05$  between varieties within a year or between annual means across all varieties or between varieties across all years

- Indicates no data available

p variety, p year and p variety x year are the p-values for the treatment terms and interactions in the table

Analysed by ANOVA with blocking for replicate (i.e. strip of land), and with plot, year and their interaction nested within replicate. Treatment terms were variety, year and their interaction. When one of the main effects was significant ( $p < 0.05$ ) post hoc t-test was conducted to compare treatment means. Significant differences are highlighted in bold.



**Table 2.** Macronutrient composition (g/100 g) of oat and barley flour of varieties grown in Orkney, between 2012 and 2014.

Crop/Variety	Ash	Protein	Starch	Sugar	NDF	$\beta$ -glucan	Fat
<b>Oats</b>							
<i>Variety means</i>							
Haga	1.55 (0.20)	9.29 (1.25)	57.64 (4.41)	2.13 (0.13)	9.16 (5.63)	2.59 (0.10) <sup>a</sup>	5.45 (0.60)
Belinda	2.39 (0.43)	9.51 (0.87)	49.32 (1.87)	5.63 (0.57)	12.82 (3.36)	3.44 (0.12) <sup>c</sup>	6.91 (0.23)
Betania	1.96 (0.13)	10.27 (0.87)	53.28 (1.65)	3.25 (0.39)	9.33 (3.12)	3.76 (0.35) <sup>d</sup>	7.33 (0.71)
Canyon	1.82 (0.15)	8.97 (0.59)	53.74 (2.72)	3.06 (0.73)	10.16 (3.34)	3.23 (0.01) <sup>bc</sup>	6.47 (0.29)
Firth	1.56 (0.13)	7.87 (0.63)	54.17 (4.34)	4.43 (0.54)	19.01 (5.38)	2.86 (0.07) <sup>ab</sup>	6.27 (0.24)
Lennon	1.68 (0.16)	9.19 (0.93)	53.06 (3.95)	5.11 (1.08)	11.40 (4.54)	3.33 (0.11) <sup>bc</sup>	6.80 (0.77)
Means	1.83 (0.13)	9.18 (0.32)	53.53 (1.09)	3.93 (0.55)	11.98 (1.52)	3.20 (0.17)	6.54 (0.26)
p variety	0.056	0.191	0.114	0.088	0.325	<b>0.001</b>	0.051
p year	<b>0.009</b>	<b>0.001</b>	<b>0.002</b>	0.572	<b>0.001</b>	0.696	<b>0.003</b>
<b>Barley</b>							
<i>Variety means</i>							
Vilde	1.42 (0.05) <sup>bc</sup>	9.82 (0.70) <sup>bc</sup>	56.03 (1.10) <sup>bc</sup>	2.79 (0.54) <sup>bc</sup>	12.99 (2.29) <sup>cde</sup>	3.11 (0.14) <sup>bc</sup>	2.84 (0.15) <sup>bc</sup>
Kannas	1.45 (0.02) <sup>c</sup>	10.38 (0.88) <sup>c</sup>	53.88 (0.18) <sup>ab</sup>	2.24 (0.65) <sup>abc</sup>	14.00 (1.65) <sup>de</sup>	3.60 (0.10) <sup>d</sup>	2.74 (0.10) <sup>abc</sup>
Vilgott	1.47 (0.06) <sup>c</sup>	9.85 (0.89) <sup>bc</sup>	53.41 (0.78) <sup>a</sup>	1.59 (0.60) <sup>ab</sup>	16.66 (2.37) <sup>e</sup>	3.45 (0.15) <sup>cd</sup>	2.84 (0.05) <sup>bc</sup>
Bere	2.19 (0.39) <sup>e</sup>	11.05 (0.18) <sup>c</sup>	54.63 (1.17) <sup>a</sup>	3.44 (0.20) <sup>c</sup>	13.76 (1.79) <sup>de</sup>	2.27 (0.07) <sup>a</sup>	3.13 (0.17) <sup>c</sup>
Concerto	1.00 (0.08) <sup>a</sup>	8.41 (0.58) <sup>a</sup>	59.24 (0.72) <sup>d</sup>	0.98 (0.72) <sup>a</sup>	8.48 (1.14) <sup>abc</sup>	2.95 (0.08) <sup>b</sup>	2.17 (0.20) <sup>a</sup>
Waggon	1.31 (0.12) <sup>abc</sup>	8.22 (0.68) <sup>a</sup>	58.56 (1.50) <sup>cd</sup>	1.33 (0.20) <sup>a</sup>	9.99 (1.87) <sup>bcd</sup>	3.07 (0.10) <sup>b</sup>	2.47 (0.15) <sup>ab</sup>
Means	1.47 (0.16)	9.62 (0.45)	55.96 (1.00)	2.06 (0.38)	12.65 (1.21)	3.08 (0.19)	2.70 (0.14)
p variety	<b>0.006</b>	<b>0.001</b>	<b>0.002</b>	<b>0.024</b>	<b>0.008</b>	<b>0.001</b>	<b>0.004</b>
p year	0.730	<b>0.001</b>	0.570	0.073	<b>0.010</b>	<b>0.013</b>	0.770

For variety means of each type of cereal, different letters down the column indicate significant differences between varieties at  $p < 0.05$ . Variety means were calculated across the 3 growing seasons. Values in brackets are standard errors  
 p variety and p year are the level of significance of these factors in the ANOVA table  
 Analysed by two-way ANOVA with variety and year as treatment factors. When the effect of variety was significant post-hoc t-test was conducted to compare treatment means. Significant differences are highlighted in bold.

**Table 3.** Abundant mineral composition (mg/ 100 g) of oat and barley flour of varieties grown in Orkney, between 2012 and 2014.

	Mg	P	K	Ca	Na	Mn	Fe	Cu	Zn
<b>Oats</b>									
<i>Variety</i>									
Haga	127.4 (5.9) <sup>cd</sup>	423.3 (17.1) <sup>b</sup>	447.5 (9.3)	71.7 (1.5) <sup>c</sup>	12.6 (2.7)	4.96 (0.08)	4.38 (0.34)	3.82 (0.37) <sup>bc</sup>	3.07 (0.15) <sup>ab</sup>
Belinda	107.3 (5.2) <sup>ab</sup>	361.1 (17.0) <sup>ab</sup>	416.0 (22.0)	49.7 (1.3) <sup>a</sup>	14.3 (3.1)	3.70 (0.40)	3.95 (0.08)	3.67 (0.96) <sup>c</sup>	2.80 (0.25) <sup>ab</sup>
Betania	108.5 (3.8) <sup>ab</sup>	372.9 (10.8) <sup>ab</sup>	387.6 (35.0)	55.6 (3.96) <sup>abc</sup>	12.7 (2.7)	4.14 (0.10)	4.28 (0.62)	4.56 (0.37) <sup>c</sup>	3.35 (0.17) <sup>bc</sup>
Canyon	108.9 (3.5) <sup>abc</sup>	373.3 (5.6) <sup>ab</sup>	443.1 (32.3)	50.9 (4.2) <sup>a</sup>	11.7 (1.5)	3.53 (0.01)	4.02 (0.29)	4.47 (0.38) <sup>c</sup>	2.59 (0.12) <sup>ab</sup>
Firth	97.5 (8.1) <sup>a</sup>	344.1 (31.7) <sup>a</sup>	402.2 (31.0)	42.8 (1.2) <sup>a</sup>	14.6 (0.9)	3.17 (0.17)	3.76 (0.39)	2.74 (0.24) <sup>ab</sup>	2.36 (0.23) <sup>a</sup>
Lennon	105.9 (5.2) <sup>ab</sup>	355.5 (9.6) <sup>ab</sup>	352.5 (11.1)	59.2 (5.1) <sup>bc</sup>	9.7 (1.8)	4.91 (0.17)	3.95 (0.20)	1.42 (0.27) <sup>a</sup>	2.21 (0.21) <sup>a</sup>
<i>Means</i>	109.3 (4.5)	371.7 (151.7)	408.2 (166.6)	54.9 (22.4)	12.6 (5.1)	4.06 (0.03)	3.95 (0.16)	3.45 (0.49)	2.73 (0.17)
<i>p variety</i>	<b>0.009</b>	<b>&lt; 0.001</b>	0.054	<b>0.020</b>	0.185	0.066	0.469	<b>&lt; 0.001</b>	<b>0.013</b>
<i>Annual</i>									
2012	109.2 (4.1) <sup>ab</sup>	379.6 (12.8) <sup>ab</sup>	379.3 (19.9) <sup>a</sup>	49.1 (4.2) <sup>a</sup>	14.5 (1.4)	4.26 (0.32)	3.91 (0.37)	3.74 (0.75)	3.15 (0.21)
2013	101.1 (5.4) <sup>a</sup>	342.7 (16.5) <sup>a</sup>	396.8 (16.7) <sup>a</sup>	56.5 (5.0) <sup>a</sup>	9.8 (1.6)	3.98 (0.48)	4.12 (0.44)	3.01 (0.52)	2.42 (0.2)
2014	118.4 (4.8) <sup>b</sup>	395.1 (12.9) <sup>b</sup>	456.2 (20.4) <sup>b</sup>	59.1 (3.7) <sup>a</sup>	14.4 (4.7)	4.09 (1.71)	3.80 (1.53)	3.95 (1.44)	2.64 (0.99)
<i>p year</i>	<b>0.005</b>	<b>0.006</b>	<b>&lt; 0.001</b>	0.195	0.340	0.190	0.603	0.094	0.153
<b>Barley</b>									
<i>Variety</i>									
Vilde	111.4 (5.5)	371.0 (18.0) <sup>ab</sup>	479.7 (27.4)	32.4 (2.4)	15.5 (1.7) <sup>bc</sup>	1.49 (0.14) <sup>bc</sup>	3.59 (0.32)	1.35 (0.32) <sup>ab</sup>	2.43 (0.43) <sup>abc</sup>
Kannas	123.7 (9.4)	416.0 (38.0) <sup>ab</sup>	559.4 (54.8)	41.7 (3.4)	17.4 (1.7) <sup>bc</sup>	1.84 (0.16) <sup>c</sup>	5.48 (0.35)	2.38 (0.39) <sup>b</sup>	3.17 (0.21) <sup>bc</sup>
Vilgott	107.2 (9.8)	352.0 (28.1) <sup>a</sup>	474.6 (39.8)	28.8 (3.1)	12.8 (3.3) <sup>abc</sup>	1.53 (0.18) <sup>abc</sup>	4.67 (0.97)	1.66 (0.38) <sup>ab</sup>	2.44 (0.35) <sup>ab</sup>
Bere	131.2 (14.5)	472.1 (52.8) <sup>b</sup>	498.3 (53.3)	43.2 (5.9)	16.8 (2.6) <sup>bc</sup>	1.92 (0.18) <sup>bc</sup>	6.48 (0.12)	3.88 (0.53) <sup>b</sup>	3.72 (0.21) <sup>c</sup>
Concerto	122.3 (11.6)	354.7 (18.7) <sup>a</sup>	477.8 (31.4)	36.3 (1.1)	8.5 (3.5) <sup>a</sup>	1.29 (0.09) <sup>a</sup>	4.84 (0.43)	1.88 (0.36) <sup>ab</sup>	2.10 (0.47) <sup>a</sup>
Waggon	104.0 (10.4)	355.2 (18.6) <sup>a</sup>	479.6 (24.9)	40.6 (6.3)	7.6 (2.3) <sup>a</sup>	1.53 (0.18) <sup>ab</sup>	4.61 (0.59)	1.88 (0.34) <sup>ab</sup>	2.41 (0.34) <sup>ab</sup>
<i>Means</i>	116.6 (47.6)	386.8 (157.9)	494.9 (202.0)	37.2 (15.2)	13.1 (5.3)	1.60 (0.09)	4.95 (0.39)	2.17 (0.37)	2.71 (0.25)
<i>p variety</i>	0.128	<b>0.045</b>	0.289	0.292	<b>0.018</b>	<b>0.013</b>	0.367	<b>0.004</b>	<b>&lt; 0.001</b>
<i>Annual</i>									
2012	115.9 (3.7) <sup>a</sup>	384.5 (12.4) <sup>a</sup>	477.9 (8.7) <sup>a</sup>	36.8 (1.6) <sup>ab</sup>	14.3 (1.0)	1.77 (0.16) <sup>b</sup>	5.96 (0.47)	2.79 (0.38)	3.29 (0.13) <sup>b</sup>
2013	98.6 (4.7) <sup>a</sup>	337.3 (16.2) <sup>a</sup>	444.6 (16.6) <sup>a</sup>	31.1 (1.6) <sup>a</sup>	10.2 (4.2)	1.29 (0.52) <sup>a</sup>	4.49 (1.82)	1.33 (0.50)	2.04 (0.84) <sup>a</sup>
2014	144.3 (8.3) <sup>b</sup>	474.1 (40.9) <sup>b</sup>	605.6 (28.7) <sup>b</sup>	44.9 (4.5) <sup>b</sup>	14.4 (5.8)	1.66 (0.70) <sup>b</sup>	4.97 (2.04)	2.35 (1.00)	2.95 (1.27) <sup>b</sup>
<i>p year</i>	<b>&lt; 0.001</b>	<b>0.007</b>	<b>&lt; 0.001</b>	<b>0.016</b>	0.312	<b>0.032</b>	0.160	0.056	<b>0.015</b>

For variety and annual means of each type of cereal, different letters down the column indicate significant differences at  $p < 0.05$ . Variety means were calculated across the 3 growing seasons, while annual means were calculated for the 6 varieties grown each year. Values in brackets are standard errors  
*p* variety and *p* year are the level of significance of these factors in the table. Significant differences are highlighted in bold.

Analysed by two-way ANOVA with variety and year as treatment factors. When the effect of variety was significant post-hoc t-test was conducted to compare treatment means

**Table 4.** Macronutrient composition (g/100 g) of oat and barley flour of varieties grown at different locations between 2012 and 2014.

Cereal/Variety	Location	Ash	Protein	Starch	Sugar	NDF	β-glucan	Fat
<b>Oats</b>								
<i>Variety x Location means</i>								
Canyon	Orkney	1.82 (0.15)	8.97 (0.59)	53.74 (2.72)	3.06 (0.73)	10.16 (3.34)	3.23 (0.01)	6.47 (0.29)
	Berwick	1.47 (0.40)	9.10 (0.49)	50.91 (2.23)	3.77 (0.63)	13.20 (2.44)	3.53 (0.11)	4.62 (1.30)
	Morfa	1.82 (0.19)	9.41 (1.28)	49.90 (5.15)	3.91 (0.84)	13.94 (6.27)	3.43 (0.20)	6.20 (0.25)
Firth	Orkney	1.56 (0.13)	7.87 (0.63)	54.17 (4.34)	4.43 (0.54)	14.39 (5.38)	2.86 (0.07)	6.27 (0.24)
	Berwick	1.77 (0.04)	8.83 (1.15)	53.26 (5.44)	5.08 (1.40)	14.40 (7.37)	3.17 (0.11)	5.44 (0.18)
	Morfa	1.44 (0.14)	10.38 (0.80)	57.64 (2.21)	4.07 (0.80)	6.53 (2.87)	3.28 (0.12)	6.06 (0.05)
Lennon	Orkney	1.68 (0.16)	9.19 (0.93)	53.06 (3.95)	5.11 (1.08)	11.40 (4.54)	3.33 (0.11)	6.80 (0.77)
	Berwick	1.66 (0.08)	10.61 (0.37)	61.11 (0.39)	4.85 (0.83)	3.86 (0.80)	3.82 (0.25)	8.26 (0.33)
	Morfa	1.60 (0.06)	10.29 (0.56)	60.42 (1.25)	5.61 (0.89)	3.49 (0.79)	3.52 (0.20)	8.25 (0.14)
<i>Variety means</i>								
Canyon		1.70 (0.12)	9.16 (0.13)	51.52 (1.15) <sup>a</sup>	3.58 (0.26) <sup>a</sup>	12.43 (1.16)	3.40 (0.11) <sup>b</sup>	5.76 (0.58) <sup>a</sup>
Firth		1.59 (0.09)	9.03 (0.73)	55.02 (1.33) <sup>ab</sup>	4.53 (0.29) <sup>ab</sup>	11.77 (2.62)	3.10 (0.10) <sup>a</sup>	5.92 (0.25) <sup>a</sup>
Lennon		1.65 (0.02)	10.03 (0.45)	58.20 (2.58) <sup>b</sup>	5.19 (0.22) <sup>b</sup>	6.25 (2.58)	3.54 (0.19) <sup>b</sup>	7.77 (0.48) <sup>b</sup>
<i>Location means</i>								
Orkney		1.69 (0.08)	8.68 (0.41)	53.65 (0.32)	4.20 (0.60)	11.98 (1.43)	3.14 (0.14) <sup>a</sup>	6.51 (0.38)
Berwick		1.63 (0.09)	9.51 (0.55)	55.10 (3.08)	4.57 (0.40)	10.49 (3.33)	3.51 (0.19) <sup>b</sup>	6.11 (1.10)
Morfa		1.62 (0.11)	10.03 (0.31)	55.98 (3.15)	4.53 (0.54)	7.99 (4.18)	3.41 (0.07) <sup>b</sup>	6.84 (0.69)
<i>Year means</i>								
2012		1.39 (0.12) <sup>a</sup>	10.72	60.55 (0.91) <sup>b</sup>	3.85 (0.44)	3.16 (0.82) <sup>a</sup>	3.26 (0.08) <sup>a</sup>	6.08 (0.63)
2013		1.79 (0.06) <sup>b</sup>	9.06 (0.38) <sup>a</sup>	51.21 (2.02) <sup>a</sup>	4.84 (0.32)	14.80 (2.33) <sup>b</sup>	3.49 (0.14) <sup>b</sup>	6.57 (0.34)
2014		1.78 (0.08) <sup>b</sup>	8.32 (0.43) <sup>a</sup>	53.47 (1.78) <sup>b</sup>	4.21 (0.76)	12.06 (2.27) <sup>b</sup>	3.34 (0.08) <sup>ab</sup>	6.80 (0.34)
p Variety		0.529	0.086	<b>0.014</b>	<b>0.039</b>	0.051	<b>0.004</b>	<b>0.001</b>
p Location		0.984	0.123	0.998	0.716	0.860	<b>0.011</b>	0.339
p Year		<b>0.029</b>	<b>0.001</b>	<b>0.003</b>	0.155	<b>0.004</b>	<b>0.035</b>	0.124
<b>Barley</b>								
<i>Variety x location means</i>								
Concerto	Orkney	1.00 (0.08)	8.41 (0.58)	59.24 (0.72)	0.98 (0.72)	8.48 (1.14)	2.95 (0.08)	2.17 (0.20)
	Dundee	0.91 (0.12)	7.97 (0.36)	61.77 (1.83)	1.94 (0.55)	6.58 (1.36)	2.80 (0.13)	2.49 (0.16)
Waggon	Orkney	1.31 (0.12)	8.22 (0.66)	58.56 (1.50)	1.33 (0.20)	9.99 (1.87)	3.07 (0.10)	2.47 (0.15)
	Dundee	1.02 (0.17)	7.82 (0.45)	60.65 (3.10)	2.25 (0.51)	7.64 (3.41)	3.11 (0.20)	2.47 (0.14)
<i>Variety means</i>								
Concerto		0.96 (0.07)	8.19 (0.32)	60.51 (1.04)	1.46 (0.46)	7.53 (0.90)	2.88 (0.08)	2.33 (0.13)
Waggon		1.11 (0.08)	8.13 (0.47)	58.87 (1.61)	1.71 (0.34)	9.63 (1.86)	3.09 (0.02)	2.54 (0.08)
<i>Location means</i>								
Orkney		1.09 (0.06)	8.42 (0.47)	58.16 (0.60)	1.07 (0.33)	10.05 (1.04)	2.99 (0.08)	2.39 (0.14)
Dundee		0.97 (0.10)	7.89 (0.26)	61.21 (1.63)	2.10 (0.34)	7.11 (1.66)	2.95 (0.13)	2.48 (0.09)
<i>Year means</i>								
2012		0.85 (0.12) <sup>a</sup>	9.15 (0.44) <sup>b</sup>	61.75 (2.14)	1.95 (0.67)	5.53 (1.66) <sup>a</sup>	2.92 (0.12)	2.38 (0.24)
2013		1.00 (0.04) <sup>b</sup>	7.89 (0.15) <sup>ab</sup>	57.27 (0.87)	1.74 (0.28)	8.97 (1.15) <sup>ab</sup>	3.14 (0.11)	2.49 (0.05)

2014	1.07	7.43 (0.24) <sup>a</sup>	60.04 (1.06)	1.07 (0.40)	11.24 (1.48) <sup>b</sup>	2.87 (0.15)	2.44 (0.09)
p Variety	0.073	0.854	0.318	0.653	0.170	0.252	0.252
p Location	0.117	0.199	0.089	0.098	0.072	0.784	0.616
p Year	<b>0.024</b>	<b>0.021</b>	0.125	0.415	<b>0.036</b>	0.383	0.873

For each type of cereal, year means in the same column followed by the same letter were not significantly different at  $p < 0.05$

Data for each cereal variety in each location are means based on three growing seasons, with standard errors given in brackets.

Where standard errors were less than 0.05, these have not been given

$p$  variety,  $p$  Location and  $p$  year are the level of significance of these factors in the table

Data were analysed by three way ANOVA with variety, year and location as treatment factors. When one of the main effects was significant ( $p < 0.05$ ) post hoc t-test was conducted to compare treatment means. Significant differences are highlighted in bold

Abbreviations: NDF Neutral Detergent Fibre; Berwick, Berwick-upon-Tweed.

**Table 5.** Mineral composition (mg /100 g) of oat and barley flour of varieties grown at different locations between 2012 and 2014.

Cereal/Variety	Location	Mg	P	K	Ca	Na	Mn	Fe	Cu	Zn
<u>Oats</u>										
<i>Variety x Location means</i>										
Canyon	Orkney	109.9 (3.5)	373.3 (6.4)	443.1 (37.3)	50.8 (4.9)	11.72 (1.70)	3.53 (0.02)	4.02 (0.34)	4.48 (0.44)	2.12 (0.55)
	Berwick	96.0 (8.5)	333.6 (16.3)	410.7 (31.5)	55.2 (7.0)	4.08 (1.61)	4.11 (0.69)	3.44 (0.53)	4.06 (1.90)	2.05 (0.55)
	Morfa	102.1 (10.3)	332.1 (39.6)	366.5 (31.9)	56.4 (6.9)	7.04 (2.14)	3.54 (0.35)	3.45 (0.60)	4.63 (1.28)	2.05 (0.55)
Firth	Orkney	97.5 (8.1)	344.3 (36.6)	402.4 (35.7)	42.7 (1.4)	14.59 (1.06)	3.17 (0.19)	3.76 (0.34)	2.74 (0.28)	2.36 (0.27)
	Berwick	108.9 (11.0)	389.5 (27.2)	442.1 (46.4)	62.9 (10.2)	2.48 (0.55)	4.73 (0.60)	4.20 (0.53)	1.48 (0.59)	1.89 (0.41)
	Morfa	102.2 (12.4)	365.2 (49.7)	382.6 (44.5)	48.8 (5.2)	6.93 (1.51)	3.25 (0.22)	3.78 (0.60)	2.88 (0.84)	2.18 (0.12)
Lennon	Orkney	105.9 (5.2)	355.5 (11.0)	352.5 (12.9)	59.1 (5.9)	9.72 (2.08)	4.91 (0.19)	3.95 (0.23)	1.42 (0.31)	1.82 (0.38)
	Berwick	89.0 (1.5)	330.1 (5.4)	352.3 (11.7)	56.4 (7.3)	1.77 (0.65)	4.60 (0.75)	3.85 (0.25)	0.60 (0.03)	2.57 (0.24)
	Morfa	103.0 (9.4)	332.7 (16.7)	309.4 (13.8)	63.5 (3.9)	5.60 (2.33)	4.57 (0.24)	3.55 (0.50)	1.30 (0.34)	1.67 (0.49)
<i>Variety means</i>										
Canyon		102.5 (2.9)	346.4 (13.1)	406.7 (22.2) <sup>b</sup>	54.1 (1.6) <sup>a</sup>	7.61 (2.22)	3.71 (0.51) <sup>a</sup>	3.63 (0.19)	4.39 (0.17) <sup>b</sup>	2.14 (0.02)
Firth		103.3 (3.7)	366.3 (13.5)	409.0 (17.4) <sup>b</sup>	51.4 (5.9) <sup>a</sup>	8.00 (3.54)	3.73 (0.19) <sup>a</sup>	3.91 (0.14)	2.37 (0.44) <sup>a</sup>	2.14 (0.14)
Lennon		99.3 (5.2)	340.4 (8.1)	338.0 (14.3) <sup>a</sup>	59.6 (2.1) <sup>b</sup>	5.69 (2.95)	4.69 (0.11) <sup>b</sup>	3.78 (0.12)	1.11 (0.26) <sup>a</sup>	2.02 (0.28)
<i>Location means</i>										
Orkney		104.2 (3.4)	357.6 (8.5)	399.3 (26.2) <sup>b</sup>	50.9 (4.7)	12.01 (1.41) <sup>b</sup>	3.87 (0.53)	3.91 (0.08)	2.88 (0.89)	2.09 (0.15) <sup>a</sup>
Berwick		97.6 (5.5)	351.1 (19.2)	401.7 (26.3) <sup>b</sup>	58.2 (2.4)	2.78 (0.68) <sup>a</sup>	4.48 (0.19)	3.82 (0.22)	2.05 (1.04)	2.17 (0.20) <sup>b</sup>
Morfa		102.4 (0.3)	343.3 (10.9)	353.8 (22.2) <sup>a</sup>	56.2 (4.2)	6.52 (0.46) <sup>a</sup>	3.78 (0.39)	3.59 (0.09)	2.94 (0.96)	1.97 (0.15) <sup>a</sup>
<i>Year means</i>										
2012		90.4 (9.2) <sup>a</sup>	336.9 (23.5) <sup>a</sup>	352.8 (15.7)	44.5 (2.5) <sup>a</sup>	6.87 (1.42)	3.98 (0.25) <sup>ab</sup>	3.22 (0.23) <sup>a</sup>	1.91 (0.42) <sup>a</sup>	2.39 (0.11) <sup>b</sup>
2013		99.2 (1.6) <sup>a</sup>	332.1 (15.9) <sup>a</sup>	370.9 (22.6)	60.0 (1.1) <sup>b</sup>	5.66 (1.58)	3.69 (0.29) <sup>a</sup>	3.91 (0.19) <sup>a</sup>	2.21 (0.55) <sup>a</sup>	1.41 (0.17) <sup>a</sup>
2014		121.5 (2.0) <sup>b</sup>	403.6 (4.1) <sup>b</sup>	453.3 (28.6)	64.8 (4.1) <sup>b</sup>	9.66 (1.56)	4.43 (0.30) <sup>b</sup>	4.24 (0.17) <sup>b</sup>	4.13 (0.72) <sup>b</sup>	2.43 (0.11) <sup>b</sup>
p Variety		0.739	0.590	0.027	0.003	0.132	<b>&lt;0.001</b>	0.306	<b>&lt;0.001</b>	0.299
p Location		0.293	0.314	<b>0.006</b>	0.177	<b>0.001</b>	0.062	0.246	0.886	<b>0.006</b>
p Year		<b>&lt;0.001</b>	<b>&lt;0.004</b>	0.448	<b>&lt;0.001</b>	0.526	<b>0.005</b>	<b>0.003</b>	<b>0.004</b>	<b>&lt;0.001</b>
<u>Barley</u>										
<i>Variety x location means</i>										
Concerto	Orkney	113.7 (5.6)	341.3 (10.5)	455.8 (18.5)	35.7 (1.0)	8.51 (4.05)	1.29 (0.11)	4.84 (0.50)	1.89 (0.42)	1.74 (0.26)
	Dundee	106.2 (6.8)	331.3 (33.8)	445.0 (34.9)	32.1 (1.6)	7.70 (3.51)	1.19 (0.21)	3.64 (0.36)	1.94 (0.35)	2.04 (0.35)

Waggon	Orkney	96.7 (4.3)	341.3 (6.1)	463.4 (13.6)	36.2 (2.8)	7.63 (2.27)	1.53 (0.18)	4.61 (0.59)	1.88 (0.34)	2.41 (0.34)
	Dundee	99.8 (6.1)	323.9 (17.9)	465.8 (27.3)	28.7 (2.2)	10.71 (7.39)	1.22 (0.24)	3.55 (0.72)	1.35 (0.21)	2.23 (0.39)
<i>Variety means</i>										
Concerto		109.9 (3.7)	336.3 (4.9)	450.4 (5.4)	33.9 (1.8)	8.11 (0.27)	1.24 (0.05)	4.24 (0.07)	1.92 (0.06)	1.89 (0.03)
Waggon		98.3 (1.6)	332.8 (8.8)	464.5 (1.2)	32.5 (3.7)	9.17 (2.56)	1.38 (0.03)	4.08 (0.06)	1.62 (0.03)	2.32 (0.05)
<i>Location means</i>										
Orkney		105.2 (8.5)	341.5 (0.2)	459.6 (3.8)	35.9 (0.2)	8.07 (0.43)	1.41 (0.12)	4.72 (0.12) <sup>a</sup>	1.88 (0.03)	2.08 (0.33)
Dundee		103.0 (3.2)	327.6 (3.7)	455.4 (10.3)	30.4 (1.7)	9.21 (1.50)	1.21 (0.02)	3.59 (0.04) <sup>b</sup>	1.65 (0.29)	2.13 (0.09)
<i>Year means</i>										
2012		104.5 (6.1) <sup>a</sup>	339.9 (17.4) <sup>a</sup>	461.8 (17.3) <sup>a</sup>	31.8 (2.3)	9.64 (3.39)	1.37 (0.17)	4.62 (0.85)	2.27 (0.23) <sup>b</sup>	2.62 (0.34) <sup>b</sup>
2013		139.2 (4.3) <sup>b</sup>	309.2 (14.8) <sup>a</sup>	436.0 (24.6) <sup>a</sup>	30.9 (1.0)	5.03 (1.24)	1.04 (0.87)	3.72 (0.26)	1.09 (0.92) <sup>a</sup>	1.42 (0.16) <sup>a</sup>
2014		95.3 (3.8) <sup>a</sup>	416.9 (0.4) <sup>b</sup>	568.9 (5.5) <sup>b</sup>	43.7 (1.9)	10.93 (5.38)	1.43 (0.87)	4.47 (0.34)	1.89 (0.18) <sup>b</sup>	2.52 (0.77) <sup>b</sup>
p Variety		0.118	0.516	0.420	0.863	0.768	0.692	0.908	0.111	0.834
p Location		0.653	0.870	0.933	0.242	0.642	0.430	<b>0.030</b>	0.268	0.608
p Year		<b>0.002</b>	<b>0.016</b>	<b>0.014</b>	0.095	0.271	0.197	0.302	<b>0.006</b>	<b>0.027</b>

For each type of cereal, variety or location means in the same column followed by the same letter were not significantly different at  $p < 0.05$

Data for each cereal variety in each location are means based on three growing seasons with standard errors in brackets. Where standard errors were less than 0.05, these have not been given

$p$  variety and  $p$  location are the level of significance of these factors in the tables

Data were analysed by three way ANOVA with variety, year and location as treatment factors. When one of the main effects was significant ( $p < 0.05$ ) post hoc  $t$ -test was conducted to compare treatment means. Significant differences are highlighted in bold

Abbreviations: Berwick, Berwick-upon-Tweed.

**Table 6.** Annual averages for the macronutrient composition (g/100 g of flour) of oat and barley varieties grown at different trial locations and correlation coefficients for macronutrient content on rainfall and degree days at each location.

Cereal/Location/Year	Rainfall (mm)	Degree days	Ash	Protein	Starch	Sugar	NDF	$\beta$ -glucan	Fat
<b>Oats</b>									
<i>Orkney</i>									
2012	479	1821	1.58 (0.18)	11.20 (0.28)	58.16 (1.42)	4.32 (0.64)	3.57 (0.97)	3.31 (0.17)	6.19 (0.65)
2013	438	1863	2.00 (0.10)	8.69 (0.98)	48.14 (2.31)	4.12 (0.68)	18.26 (1.42)	3.29 (0.23)	7.11 (0.89)
2014	392	1862	1.87 (0.21)	8.33 (0.83)	53.49 (2.02)	5.23 (1.21)	13.21 (1.74)	3.08 (0.13)	7.34 (0.29)
Correlation coefficient, rainfall (n=18)			-0.341	0.826	0.646	-0.249	-0.740	0.009	-0.668
Correlation coefficient, degree days (n=18)			0.474	-0.793	-0.740	0.181	0.830	-0.032	0.669
p-value, correlation coefficient rainfall			0.179	<b>&lt;0.001</b>	<b>0.005</b>	0.334	<b>&lt;0.001</b>	0.972	<b>0.003</b>
p-value, correlation coefficient degree days			0.054	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.486	<b>&lt;0.001</b>	0.902	<b>0.003</b>
<i>Berwick-upon-Tweed</i>									
2012	637	2369	1.37 (0.35)	10.38 (0.39)	59.49 (2.25)	4.26 (1.17)	5.01 (1.82)	3.31 (0.15)	5.44 (1.91)
2013	230	2110	1.71 (0.09)	9.97 (0.44)	54.40 (4.15)	5.48 (0.48)	10.60 (4.18)	3.80 (0.27)	6.27 (0.69)
2014	327	1886	1.82 (0.02)	8.20 (0.97)	51.40 (4.92)	4.01 (1.17)	15.86 (6.63)	3.38 (0.19)	6.61 (0.98)
Correlation coefficient, rainfall (n=9)			-0.482	0.324	0.422	-0.224	-0.414	-0.472	-0.232
Correlation coefficient, degree days (n=9)			-0.493	0.698	0.494	0.117	-0.552	-0.028	-0.239
p-value, correlation coefficient rainfall			0.189	0.394	0.257	0.561	0.268	0.199	0.561
p-value, correlation coefficient degree days			0.177	<b>0.036</b>	0.176	0.763	0.123	0.942	0.534
<i>Morfa</i>									
2012	568	2039	1.38 (0.18)	11.52 (0.15)	60.64 (1.35)	3.88 (0.90)	2.93 (0.65)	3.35 (0.19)	7.00 (0.65)
2013	236	1795	1.84 (0.16)	8.65 (0.91)	51.42 (6.12)	5.21 (0.89)	14.14 (6.57)	3.38 (0.24)	6.72 (0.88)
2014	301	1770	1.61 (0.10)	9.47 (0.11)	54.96 (1.89)	3.95 (1.11)	8.43 (2.00)	3.49 (0.02)	6.82 (0.60)
Correlation coefficient, rainfall (n=9)			-0.621	0.841	0.567	-0.279	-0.593	-0.760	0.111
Correlation coefficient, degree days (n=9)			-0.540	0.790	0.515	-0.189	-0.513	-0.726	0.102
p-value, correlation coefficient rainfall			0.073	<b>0.044</b>	0.111	0.467	0.092	<b>0.017</b>	0.776
p-value, correlation coefficient degree days			0.137	<b>0.011</b>	0.156	0.624	0.157	<b>0.026</b>	0.793
<b>Barley</b>									
<i>Orkney</i>									
2012	479	1821	1.31 (0.11)	11.00 (0.39)	55.83 (1.01)	1.53 (0.37)	10.88 (1.44)	3.38 (0.17)	2.80 (0.22)
2013	438	1863	1.40 (0.18)	8.88 (0.35)	55.04 (2.49)	2.67 (0.12)	14.90 (3.02)	3.28 (0.21)	2.76 (0.12)
2014	392	1862	1.39 (0.11)	8.9 (0.47)	55.61 (0.99)	1.76 (0.45)	14.09 (1.15)	3.03 (0.15)	2.69 (0.15)
Correlation coefficient, rainfall (n=18)			0.121	0.670	0.812	-0.171	-0.475	0.238	0.096
Correlation coefficient, degree days (n=18)			-0.123	-0.701	-0.111	0.272	0.518	-0.185	-0.079
p-value, correlation coefficient rainfall			0.633	<b>0.002</b>	0.749	0.496	<b>0.045</b>	0.339	0.704
p-value, correlation coefficient degree days			0.628	<b>0.001</b>	0.658	0.274	<b>0.027</b>	0.461	0.753
<i>Dundee</i>									
2012	550	1857	0.69 (0.00)	8.43 (0.09)	65.44 (0.39)	3.11 (0.12)	2.83 (1.06)	2.72 (0.05)	2.50 (0.28)
2013	293	1837	1.17 (0.08)	8.15 (0.05)	56.91 (1.81)	1.57 (0.47)	10.92 (2.66)	3.21 (0.17)	2.50 (0.05)
2014	335	1967	1.05 (0.08)	7.10 (0.18)	61.29 (0.26)	1.63 (0.12)	7.59 (0.00)	2.94 (0.35)	2.45 (0.21)
Correlation coefficient, rainfall (n=6)			-0.951	0.531	0.884	0.922	-0.862	-0.607	0.036
Correlation coefficient, degree days (n=6)			0.123	-0.921	0.150	-0.314	-0.379	-0.125	-0.101
p-value, correlation coefficient rainfall			<b>0.003</b>	0.277	<b>0.019</b>	<b>0.008</b>	<b>0.027</b>	0.201	0.945
p-value, correlation coefficient degree days			0.816	<b>0.009</b>	0.776	0.543	0.943	0.813	0.849

Values are the average annual macronutrient content for each cereal at each site. Values in brackets are standard errors.

Abbreviations: NDF Neutral Detergent Fibre

n=number of data pairs.

Correlations with rainfall and degrees days with the macronutrient content for oat and barley varieties grown at different trial locations.

Significant differences are highlighted in bold where  $p < 0.05$ .

## 7. Supplementary Information

**Table S1.** Summary of planting dates, fertilizer regime and herbicide application to oat and barley trials in Orkney, from 2012 to 2014.

Year	Planting Date	Barley fertilization (kg ha <sup>-1</sup> )	Oat fertilization (kg ha <sup>-1</sup> )	Herbicide (chemical and date of application)
2012	1 May	N 65, P 65, K 105	N 60, P 60, K 97	Tomahawk (0.75 L ha <sup>-1</sup> (fluroxypyr-meptyl, 200 g L <sup>-1</sup> ); Ally Max (20 g ha <sup>-1</sup> (143 g kg <sup>-1</sup> metsulfuron methyl and 143 g kg <sup>-1</sup> tribenuron methyl). Applied on 20 June.
2013	4 April	N 65, P 65, K 105	N 50, P 50, K 81	As for 2012. Applied on 17 June.
2014	21 April	N 65, P 65, K 87	N 50, P 50, K 67	Ally Max (20 g ha <sup>-1</sup> (143 g kg <sup>-1</sup> metsulfuron methyl and 143 g kg <sup>-1</sup> tribenuron methyl). Applied on 1 June.

**Table S2.** Summary of soil analyses for oat and barley trials in Orkney, from 2012 to 2014.

Analysis	Barley			Oats		
	2012	2013	2014	2012	2013	2014
pH	6.4	6.1	6.7	6.7	6.5	6.3
Available P (mg/l)	28.4	21.4	28.0	25.0	27.0	31.4
Available K (mg/l)	89	58	99	71	64	115
Available Mg (mg/l)	119	97	94	103	101	103
EDTA Extractable Copper (mg/l)	2.7	2.9	3.5	3.0	3.0	3.7
Hot water soluble Boron (mg/l)	0.8	0.6	0.7	0.8	0.6	0.9
EDTA Extractable Zinc (mg/l)	1.5	1.2	1.5	1.5	1.6	1.7
DPTA Extractable Iron (mg/l)	276.7	223.8	209.0	212.7	211.8	283.3
Available (Phosphate Buffer Soluble) Sulphate (mg/l)	29.2	40.8	30.0	31.2	34.9	28.6
DPTA Extractable Manganese (mg/l)	6.7	11.4	20.3	5.2	9.3	32.5



**Table S3.** Monthly average temperature (°C) and rainfall (mm) for 2012 to 2014 for oat and barley trial sites.

Location	Variable	Year	April	May	June	July	August	September
Orkney	Temperature	2012	6.2	8.4	10.4	12.4	13.6	11.2
Orkney	Temperature	2013	6.0	8.7	11.8	14.6	14.1	12.3
Orkney	Temperature	2014	8.3	10.0	12.9	14.5	13.6	13.2
Orkney	Rainfall	2012	82	36	45	36	89	137
Orkney	Rainfall	2013	68	53	37	42	69	127
Orkney	Rainfall	2014	48	44	45	46	124	68
Dundee	Temperature	2012	5.5	8.4	10.5	12.9	14.0	11.6
Dundee	Temperature	2013	7.6	11.4	12.2	15.7	14.3	11.9
Dundee	Temperature	2014	8.3	10.3	13.3	15.0	12.7	13.8
Dundee	Rainfall	2012	97	66	134	123	87	44
Dundee	Rainfall	2013	31	51	43	52	29	36
Dundee	Rainfall	2014	37	58	63	41	114	18
Berwick-upon-Tweed	Temperature	2012	6.3	9.3	11.9	13.5	14.8	11.8
Berwick-upon-Tweed	Temperature	2013	6.6	10.1	13.1	16.7	15.3	12.5
Berwick-upon-Tweed	Temperature	2014	9.0	11.2	14.6	15.8	13.6	13.8
Berwick-upon-Tweed	Rainfall	2012	96	79	144	129	93	82
Berwick-upon-Tweed	Rainfall	2013	43	55	24	24	27	53
Berwick-upon-Tweed	Rainfall	2014	57	91	58	34	86	26
Morfa	Temperature	2012	7.1	11.0	12.7	13.8	15.4	12.7
Morfa	Temperature	2013	6.9	9.1	12.9	16.9	15.5	13.8
Morfa	Temperature	2014	10.0	11.2	13.9	16.1	14.5	14.8
Morfa	Rainfall	2012	90	80	146	73	102	81
Morfa	Rainfall	2013	34	59	44	35	64	62
Morfa	Rainfall	2014	63	66	55	20	97	17

**Table S4.** Comparison of the macronutrient content (mg/100 g) of flour from grains of Vilde barley and Haga oats from different plots of the Orkney trial in 2012.

Cereal and plot number	Ash	Protein	Starch	Sugar	NDF	Fat
Vilde Barley 36	1.94	9.61	58.64	3.27	18.36	3.06
Vilde Barley 40	1.98	9.94	57.74	4.19	20.47	2.98
Vilde Barley 43	1.98	9.50	58.36	3.73	20.04	3.13
Vilde Barley 53	1.94	9.66	58.93	3.65	18.81	3.01
Vilde Barley 58	1.86	8.64	59.76	3.25	18.86	3.04
Haga Oats 5	2.55	8.08	49.65	3.36	22.99	5.35
Haga Oats 9	2.60	7.88	47.85	2.33	25.79	5.21
Haga Oats 17	2.48	7.47	48.95	2.35	24.19	5.36
Haga Oats 21	2.48	7.49	48.47	2.57	25.56	5.23
Haga Oats 26	2.50	7.59	48.54	3.28	25.57	5.12

**Table S5.** Trace elements in oat and barley grains ( $\mu\text{g}/100\text{ g}$  of flour) of varieties grown in Orkney between 2012 and 2014.

Oat variety	Cr	Co	Ni	Se	Mo	Cd	Pb
Haga	Trace	Trace	1.0 (0.2)	Trace	0.6 (0.1) <sup>b</sup>	Trace	Trace
Belinda	0.2 (0.1)	0.3 (0.2)	1.0 (0.2)	Trace	0.4 (0.0) <sup>ab</sup>	Trace	Trace
Betania	0.1 (0.0)	0.7 (0.4)	1.2 (0.3)	Trace	0.4 (0.1) <sup>ab</sup>	Trace	Trace
Canyon	0.1 (0.0)	3.6 (3.1)	3.6 (2.3)	Trace	0.4 (0.1) <sup>ab</sup>	Trace	Trace
Firth	0.3 (0.2)	0.3 (0.2)	0.9 (2.0)	Trace	0.3 (0.1) <sup>a</sup>	Trace	0.9 (0.8)
Lennon	Trace	0.1 (0.1)	1.1 (0.2)	Trace	0.4 (0.1) <sup>a</sup>	Trace	Trace
<b>P variety</b>	0.783	0.533	0.336	-	< 0.001	-	-
<b>P year</b>	0.722	0.357	0.537	-	0.119	-	-
Barley variety	Cr	Co	Ni	Se	Mo	Cd	Pb
Vilde	0.0 (0.0)	0.1 (0.0)	0.1 (0.0)	Trace	0.2 (0.0)	Trace	0.1 (0.1)
Kannas	0.2 (0.1)	1.0 (0.8)	0.1 (0.0)	Trace	0.2 (0.1)	Trace	Trace
Vilgott	0.1 (0.1)	0.2 (0.1)	0.1 (0.0)	Trace	0.2 (0.0)	Trace	Trace
Bere	0.2 (0.1)	0.8 (0.3)	1.2 (1.0)	Trace	0.3 (0.1)	0.1 (0.0)	0.1 (0.0)
Concerto	0.2 (0.1)	0.2 (0.1)	0.1 (0.0)	Trace	0.2 (0.0)	Trace	Trace
Waggon	0.7 (0.5)	1.0 (0.6)	0.3 (0.2)	Trace	0.3 (0.0)	Trace	Trace
<b>P variety</b>	0.468	0.650	0.243	-	0.232	-	-
<b>P year</b>	0.100	0.030	0.183	-	0.002	-	-

Table presents means based on three growing seasons with standard errors in brackets

Different letters indicate significant differences between varieties at  $P < 0.05$ .

P variety and P year are the level of significance of these factors in the ANOVA tables

Where error is  $< 0.05$  expressed as 0.0

Trace indicates levels below detection limits

**Table S6.** Trace element content of oat and barley grains ( $\mu\text{g}/100\text{ g}$  of flour) of varieties from trials at different locations between 2012 and 2014.

Variety	Location	Cr	Co	Ni	Se	Mo <sup>‡</sup>	Cd	Pb
<b>Canyon Oats</b>	<b>Orkney</b>	Trace	6.2 (3.6)	4.6 (2.7)	Trace	0.1 (0.1)	Trace	0.1 (0.0)
	<b>Berwick</b>	Trace	0.1 (0.0)	0.4 (0.2)	Trace	0.1 (0.0)	Trace	Trace
	<b>Morfa</b>	0.1 (0.1)	1.1 (0.6)	0.3 (0.2)	Trace	0.1 (0.0)	Trace	0.1 (0.0)
<b>Canyon Mean</b>		Trace	2.5 (1.9)	1.8 (1.4)	Trace	0.1 (0.0)	Trace	0.1 (0.0)
<b>Firth Oats</b>	<b>Orkney</b>	0.4 (0.2)	0.4 (0.2)	0.4 (0.3)	Trace	0.1 (0.1)	Trace	1.6 (0.9)
	<b>Berwick</b>	Trace	0.5 (0.3)	0.3 (0.2)	Trace	0.1 (0.1)	Trace	Trace
	<b>Morfa</b>	1.3 (0.7)	1.7 (1.0)	Trace	Trace	0.1 (0.1)	Trace	Trace
<b>Firth Mean</b>		0.6 (0.4)	0.9 (0.4)	0.2 (0.1)	Trace	0.1 (0.0)	Trace	0.5 (0.5)
<b>Lennon Oats</b>	<b>Orkney</b>	Trace	0.2 (0.1)	0.3 (0.2)	Trace	0.1 (0.1)	Trace	Trace
	<b>Berwick</b>	0.8 (0.6)	1.5 (0.5)	Trace	Trace	0.1 (0.1)	Trace	Trace
	<b>Morfa</b>	Trace	0.8 (0.5)	0.3 (0.2)	Trace	0.1 (0.1)	Trace	Trace
<b>Lennon Mean</b>		0.3 (0.3)	0.8 (0.4)	0.2 (0.1)	Trace	0.1 (0.0)	Trace	Trace
<b>Orkney Oats Mean</b>		0.1 (0.1)	2.3 (2.0)	1.7 (1.4)	Trace	0.1 (0.0)	Trace	0.6 (0.5)
<b>Berwick Oats Mean</b>		0.3 (0.3)	0.7 (0.4)	0.2 (0.1)	Trace	0.1 (0.0)	Trace	Trace
<b>Morfa Oats Mean</b>		0.5 (0.4)	1.2 (0.3)	0.2 (0.1)	Trace	0.1 (0.0)	Trace	Trace
<b>Concerto Barley</b>	<b>Orkney</b>	0.2 (0.1)	0.2 (0.2)	0.1 (0.1)	Trace	0.2 (0.0)	Trace	Trace
	<b>Dundee</b>	0.1 (0.0)	0.1 (0.1)	Trace	Trace	0.2 (0.0)	Trace	Trace
<b>Concerto Mean</b>		0.2 (0.0)	0.2 (0.0)	0.1 (0.0)	Trace	0.2 (0.0)	Trace	Trace
<b>Waggon Barley</b>	<b>Orkney</b>	0.7 (0.6)	0.9 (0.6)	0.3 (0.2)	Trace	0.3 (0.0)	Trace	Trace
	<b>Dundee</b>	0.1 (0.1)	1.7 (1.5)	1.1 (1.0)	Trace	0.3 (0.1)	Trace	Trace
<b>Waggon Mean</b>		0.4 (0.2)	0.6 (0.3)	0.7 (0.3)	Trace	0.3 (0.0)	Trace	Trace
<b>Orkney Barley Mean</b>		0.5 (0.2)	0.6 (0.3)	0.2 (0.1)	Trace	0.3 (0.0)	Trace	Trace
<b>Dundee Barley Mean</b>		0.1 (0.0)	0.9 (0.7)	0.6 (0.4)	Trace	0.3 (0.0)	Trace	Trace

<sup>‡</sup> Indicates a significant effect ( $P < 0.05$ ) attributable to barley variety in the ANOVA table.

Data for each cereal cultivar in each location are means based on three growing seasons with standard errors in brackets

Where error is  $< 0.05$  error expressed as 0.0

Trace below detection limit

Abbreviation: Berwick, Berwick-upon-Tweed.

**Highlights**

- Oat and barley varieties were grown in a northern maritime environment in Orkney
- Barley required fewer days and degree days from planting to harvest than oats
- In both cereals, the highest levels of  $\beta$ -glucan occurred in Scandinavian varieties
- Oats from Orkney had lower  $\beta$ -glucan and higher sodium than from more southerly trials